

COMMENTS ON TNT EQUIVALENCE

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ABSTRACT

The term "TNT Equivalence" is used throughout the explosives and related industries to compare the effects of the output of a given explosive to that of TNT. This is done for technical design reasons in scaling calculations such as for the prediction of blast waves, craters, and structural response, and is also used as a basis for government regulations controlling the shipping, handling and storage of explosive materials, as well as for the siting and design of explosive facilities.

TNT equivalence is determined experimentally by several different types of tests, the most common of which include: plate dent, ballistic mortar, trauzl, sand crush, and air blast. All of these tests do not necessarily measure the same output property of the sample explosive. As examples of this, some tests depend simply upon the CJ pressure, some depend upon the PV work in the CJ zone and in the Taylor (expansion) wave behind the CJ plane, some are functions of the total work which includes that from secondary combustion in the air mixing region of the fireball and are acutely effected by the shape of the pressure-time profile of the wave. Some of the tests incorporate systematic errors which are not readily apparent, and which have a profound effect upon skewing the resultant data. Further, some of the tests produce different TNT Equivalents for the same explosive which are a function of the conditions at which the test is run.

This paper describes the various tests used, discusses the results of each test and makes detailed commentary on what the test is actually measuring, how the results may be interpreted, and if and how these results can be predicted by first principals based calculations. Extensive data bases are referred to throughout the paper and used in examples for each point in the commentaries.

This paper concludes with recommendations of where TNT Equivalents might be dropped in favor of actual performance data, and will provide cautions where use of TNT Equivalents may produce problems or erroneous engineering results.

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BACKGROUND

The term "TNT Equivalence" has been in common parlance for a long time in the explosives field, both by the military as well as in industry. It was first used apparently to describe the output characteristics of explosives by comparison to those of TNT because there did not exist a commonly understood way to specify the various aspects of explosive behavior. TNT equivalence was (and still is) measured experimentally by several different tests which vary somewhat from laboratory to laboratory and from country to country. These tests basically are all similar to tests described in Ref I, and these are the "Sand Crush", the "Trauzl (lead block)", the "Ballistic Mortar", the "Plate Dent", and the "Air Blast" tests. Each test measures some empirically measured output effect and compares this to an equivalent weight of TNT which would produce the same observed effect. A problem arises because the TNT equivalence determined by the various tests do not agree with each other, and in some of the tests the equivalence is strongly influenced by the conditions at which the particular test was conducted.

TNT equivalence is used as a basis for several important government regulatory issues which include limits imposed upon the size and location of explosive storage facilities, siting and construction of explosive manufacturing facilities, and the packaging and transportation of explosives. TNT equivalence is also used by scientists, engineers and analysts in engineering scaling calculations involving air blast, cratering, structural response, and physiological effects. The variability of determination of TNT equivalence causes a serious problem in these areas. The following material will describe these basic tests and show the degree of variability within each particular test and also that between the types of tests.

THE SAND CRUSH TEST

The description of this test is here quoted from Ref. 1. *"A 0.4 gram sample of explosive, pressed at 3000 pounds per square inch in to a No. 6 cap, is initiated by lead azide, or mercury fulminate (or if necessary, by lead azide and tetryl), in a sand test bomb containing 200 gm of "on 30 mesh" Ottawa sand. The amount of azide, or of tetryl, that must be used to insure that the sample crushes the maximum net weight of sand, is designated as its sensitivity to initiation and the net weight of sand crushed finer than 30 mesh is termed the sand crush value. The net weight of sand crushed is obtained by subtracting from the total the amount crushed by the initiator when shot alone."*

The process of crushing, or shattering, the sand is obviously dependent upon the shock pressure imparted to it by the explosive. We should expect then that the sand crush value is related directly to the peak (or CJ) pressure of the explosive. However, the density and thus the CJ pressure, is neither specified nor reported in the results of this test. Although the explosive is always pressed at 3000 psi, this produces a different density for each type. Also, a considerable amount of energy is lost in shock heating, expansion, fracturing, and accelerating the metal cap. This energy loss is approximately linearly proportional to the CJ pressure of the explosive and is therefore different for each explosive and is not compensated for in the results. Thus we cannot correlate these test results to either the CJ pressure or to the

energy in the CJ state. We can examine how the sand test results correlate to the heat energy released by the explosive, as expressed by the heat of explosion, and this is shown in Figure 1. However this parameter only relates to a part of the energy available from the detonation and does not reflect upon the

power, the rate of the release of the energy. Figure 1 shows the sand crush values for a number of explosives plotted against the heat of explosion. It is apparent that this test cannot be easily or reasonably correlated to any of the known explosives output power or energy characteristics. If we wish to express the "shattering ability" of an explosive, then it is far more reasonable to merely give its CJ pressure. The CJ pressure can be quite accurately estimated when one knows the density and detonation velocity (Ref. 2), both obtained by rather simple straight forward and accurate means. Table 1 is the list of explosives for which data appears in this figure as well as those in figures 2 and 3.

Fig. 1. Sand Crush Value versus the Heat of Explosion

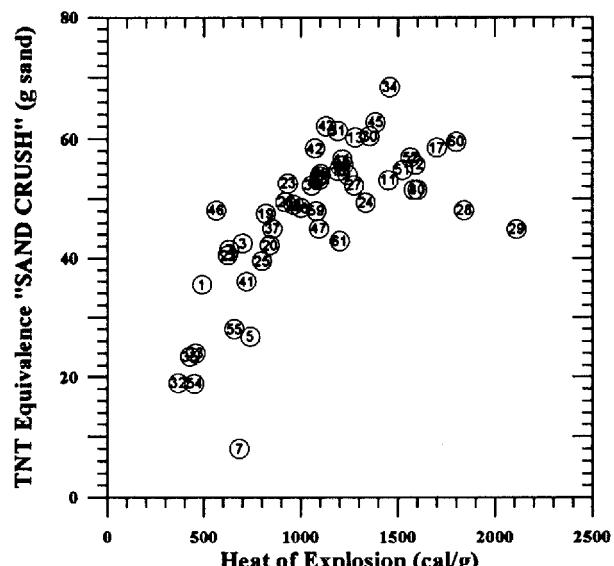


Fig. 1. Sand Crush Value versus the Heat of Explosion

Table 1. EXPLOSIVES SHOWN IN FIGURES 1 THROUGH 3

1. amatol(80/20)	17. dbx	33. lead styphnate	49. pipe
2. amatol(60/40)	18. datnb	34. nitromannite	50. plumbatol
3. amatol(50/50)	19. ddnp	35. mercury fulminate	51. ptx-1
4. AN(neat)	20. degn	36. minol-2	52. ptx-2
5. baratol(67/33)	21. dnt	37. nc(12.6%n)	53. ripe
6. baronal	22. lvd dynamite	38. nc(13.45%n)	54. silver azide
7. black powder	23. mvd dynamite	39. nc(14.14%n)	55. tetracene
8. comp a-3	24. ednatol(55/45)	40. nitroglycerine	56. tetryl
9. comp b	25. explosive d	41. nitroguanidine	57. tetrytol(75/25)
10. comp c-2	26. h6	42. octol(70/30)	58. tetrytol(70/30)
11. comp c-3	27. edna	43. octol(75/25)	59. tnt
12. comp c-4	28. hbx-1	44. pentolite(50/50)	60. torpex
13. rdx	29. hbx-3	45. petn	61. tatb
14. cyclotol(70/30)	30. hmx	46. picramide	62. tritonal(80/20)
15. cyclotol (65/35)	31. hta-3	47. picratol(52/48)	
16. cyclotol(60/40)	32. lead azide	48. picric acid(pressed)	(data from Ref. 1)

Table 1. EXPLOSIVES SHOWN IN FIGURES 1 THROUGH 3

THE TRAUZL (lead block) TEST

The description of this test is here quoted from Ref. 1. *"A sample of the explosive to be tested (of the order of 10 gm) is exploded in a cavity, or borehole, 25-mm in diameter and 125-mm deep, in a lead block 200-mm in diameter and 200-mm in height. The borehole is made centrally in the upper face of each block, which is cast in a mold from desilverized lead of the best quality. Although these tests have been made under a variety of conditions, where possible the data have been taken from or related to those of Naoum (Ph. Naoum, Z ges Schiess-Sprengstoffw(sic), 27 June 1932). Here a No. 8 blasting cap was used for initiation of the sample contained in glass. The weight of the sample used was adjusted to give, with the initiator, a total expansion of 250 to 300 cc, since within this range expansion and sample weight were linearly related under the conditions of Naoum's test. Thus expansions for equivalent weights were readily calculated, and the test value expressed in percent of the expansion of an equivalent weight of TNT"*

The expansion, or springing, of the lead borehole is a plastic flow, and therefore, a hydrodynamic process. Such processes are dependent entirely upon the shock pressures in the material, and hence, upon the CJ pressure of the explosive. Here again we encounter the problem that the density of the explosive is neither controlled, measured, nor reported for these tests. We therefore cannot tell what the CJ pressure would be and cannot, therefore correlate data from these tests with the known controlling parameter. Attempts have been made to estimate the results of this tests by correlation with the heat of explosion, but as mentioned previously, this parameter does not relate to the output power of the explosive. Figure 2 shows the results of the Trauzl test plotted against the heat of explosion, and as expected there is very poor correlation. Again, as with shattering ability, the "springing ability" of an explosive is certainly a function only of it's CJ pressure, and should be expressed as that pressure and not through an uncontrolled test such as this.

Figure 2.
TNT Equivalence as given by the Trauzl test plotted versus Heat of Explosion

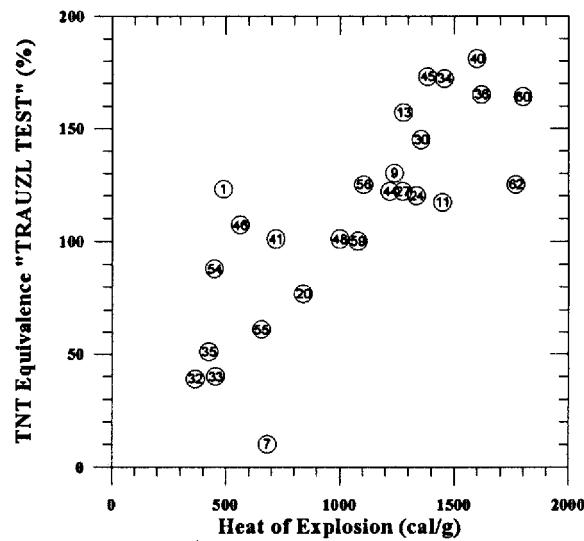


Figure 2. TNT Equivalence as given by the Trauzl test plotted versus Heat of Explosion

THE BALLISTIC MORTAR TEST

The description of this test is here quoted from Ref 1. *"The amount of sample under test which is necessary to raise the heavy ballistic mortar to the same height to which it is raised by 10 gm of TNT is determined.... The ballistic mortar consists of a long compound supporting rod, at the end of which is supported a heavy short-nosed mortar. The mortar contains a chamber about 6 inches in diameter and 1 foot long. A projectile occupies about 7 inches of the chamber and the sample to be tested occupies a small portion of the remainder of the chamber. When the sample is detonated, the projectile is driven into a sand bank, and the mortar swings through an angle which is marked on paper by a pencil attached to the mortar. The angle thus indicates the height to which the pendulum is raised by the explosion, and this latter represents the energy measured by this test procedure."*

Here, there are two effects in play: first, is the possible shock heating and plastic deformation of the end of the projectile (if the explosive was in contact with it), and second, the PV work of the hot detonation gasses as they expand to drive the projectile out of the mortar. Again we are faced with a test which neither specifies nor reports the density of the explosive sample as loaded. The loss of energy to the hydrodynamic effects, shock heating and deformation, are roughly proportional to the CJ pressure and would therefore skew the tests by having higher losses for the higher CJ pressure samples. The work in expansion is another story. In an ideal explosive, essentially all of the chemical reaction is completed in the CJ zone and the gasses expand isentropically from that point on down. Therefore, for such explosives we should be able to calculate the work in expansion if we can estimate the expansion isentrope. Estimating the isentrope is not a simple task and even more complicated by the previously mentioned deformation losses. In a non-ideal explosive, only part of the chemical reaction is completed in the CJ zone, the balance of the reactions are completed in the expansion (Taylor wave) behind the CJ plane. This means that the expansion is not isentropic since the chemical reaction is producing additional energy during the expansion. Thus these explosives release the usable expansion energy differently than do TNT or other ideal explosives. Explosives which contain metallic components such as aluminum have additional reactions later in the expansion when they mix with air, however this energy is not available to drive either the projectile or the mortar because it is released after the projectile has exited and the gasses are expanding and mixing outside of the mortar. For these reasons (and that we don't know the sample density) we cannot expect to correlate the data from the ballistic mortar to a single simple parameter such as the CJ pressure alone or the PV energy in the CJ zone.

The thermal energy in the explosive which is represented by the heat of explosion is, again, only part of the energy available. It does not account for the additional PV energy which is derived from the creation of the gasses in the detonation products. We therefore should not be able to correlate the ballistic mortar results with this parameter either, as is seen in Figure 3.

The results of the ballistic mortar tests are now seen to be very specific to the test instrument and not very good at describing the behavior of the sample explosive in any other configuration or environment.

Figure 3.
TNT Equivalence from Ballistic Mortar tests versus Heat of Explosion

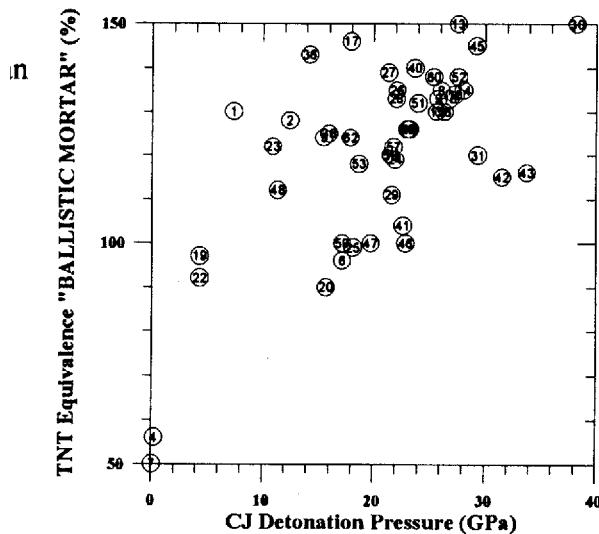


Figure 3. TNT Equivalence from Ballistic Mortar tests versus Heat of Explosion

THE PLATE DENT TEST

There are two different configurations of this test described in Ref 1, in the first, Method A, a cylinder of test explosive sample is placed on top of a 5/8 inch thick steel plate which is supported on a hollow steel cylinder. This test is not used very often because the results are a plate which is dished and has a plastically deformed dent in the bottom of the dish, thus making analysis of the results difficult to define. The second, Method B, is the preferred test and is described in that reference as "A 1-5/8-inch diameter, 5-inch long uncased charge is fired on a 1-3/4-inch thick, 5-square inch cold-rolled steel plate, with one or more similar plates as backing. The charge is initiated with a No. 8 detonator and two 1-5/8-inch diameter, 30 gm tetryl boosters."

The depth of the resulting dent formed in the plate is measured and the results of the test are reported either simply as the measured depth or as the relative brisance which is defined as 100 times the ratio of the depth of dent for the sample divided by the depth of dent produced by a TNT charge at 1.61 gm/cm³ density. Other laboratories perform similar tests but may use different charge diameters and lengths.

Changing the dimensions of the charge does not inhibit the comparison of data because the dents produced scale well with the charge dimensions. The length to diameter ratio (LID) is important in that short charges produce shallower dents. The depth of dent approaches a constant maximum value when charge LID is greater than two. This effect is shown in Figure 4, where data from Ref. 3 for three different diameters of TNT charges are plotted in the scaled, non-dimensional form.

Figure 4. Scaled dent as a function of scaled length for TNT charges

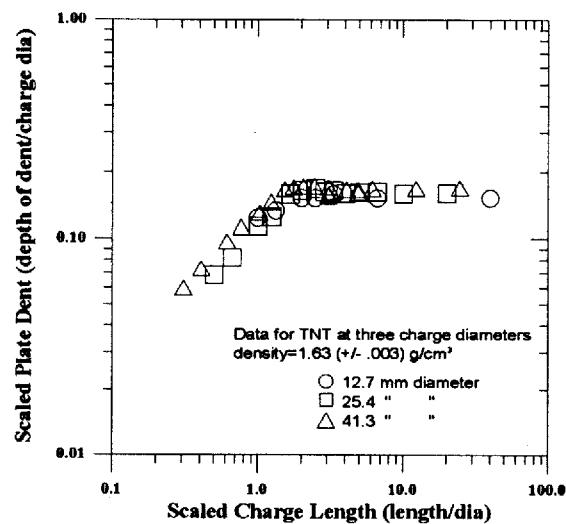


Figure 4. Scaled dent as a function of scaled length for TNT charges

Figure 5. Scaled dent versus CJ Pressure for a number of different explosives

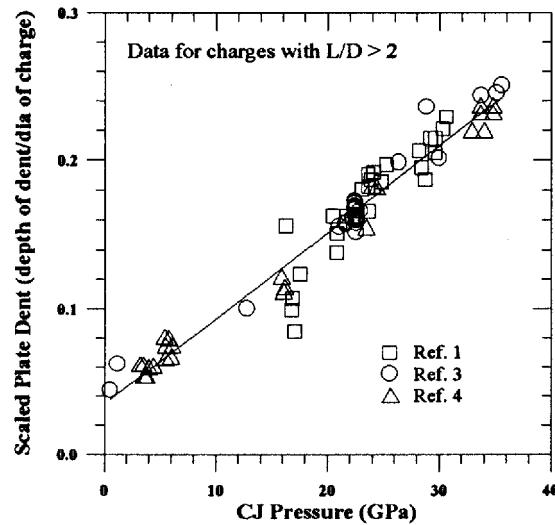


Figure 5. Scaled dent versus CJ Pressure for a number of different explosives

Using only data for charges of LID greater than two we can now compare the dent data from various sources. Since the dent data is customarily presented along with the charge density, we can now also compare this data to the CJ pressure which should be the only governing parameter (assuming the same type of steel is used in all of the tests). This is shown in Figure 5. The data in this figure are for the explosives listed in Table 2.

Table 2. EXPLOSIVES SHOWN IN FIGURE 5

EXPLOSIVE	REF	EXPLOSIVE	REF	EXPLOSIVE	REF	EXPLOSIVE	REF
amatol(50/50)	(1)	dbx	(1)	pbx-9404	(4)	tatb	(3)
baratol(73/23)	(1)	detasheet c	(4)	pentolite(50/50)	(1)	tetryl	(1)
comp a-3	(1)	ednatol(52/48)	(1)	petn	(3)	tetryl	(3)
comp b	(1)	hmx	(3)	picratol(52/48)	(1)	tetrytol(70/30)	(1)
comp c-2	(1)	iremite	(4)	pipe	(1)	tetrytol(75/25)	(1)
comp c-3	(1)	kinestick	(4)	ptx-1	(1)	tnt(cast)	(1)
comp c-4	(4)	minol-2	(1)	ptx-2	(1)	tnt(pressed)	(3)
comp c-4	(1)	nm	(3)	pyx	(3)	torpex	(1)
cyclitol(60/40)	(1)	ng	(3)	rdx	(3)	tritonal(80/20)	(1)
cyclitol(70/30)	(1)	nq	(3)	ripe	(1)		

Table 2. EXPLOSIVES SHOWN IN FIGURE 5

We see in Figure 5 that the dent test correlates to CJ pressure, and indeed in some laboratories this test is used as an independent measure of the CJ pressure. For the purposes of TNT equivalence however, the test is superfluous because it only tells us the CJ pressure.

THE AIR BLAST TEST

The air blast test, as reported in Ref 1, uses large steel cased charges fired in an open arena. Electronic pressure gauges are deployed at various convenient locations and record the pressure versus time data. The charges are suspended a sufficient height above the ground to preclude energy losses to cratering and serious ground reflection problems. The casing weight to charge weight ratio is in the neighborhood of one. Two different TNT equivalents are reported, one based on the peak blast wave pressure, and the other on the impulse. The equivalence is determined by the weight of TNT which would produce the same peak pressure (or impulse) at the same distance from the charge as that measured for the test charge.

In Table 3, it is seen that for some of the explosives shown, there are large differences in predicting the TNT equivalence as obtained from tests. These differences are large both in the positive as well as in the negative direction. Part of the reason for this is due to the energy which is lost to the steel casing in which the explosive was loaded. For example, for a TNT charge loaded into a steel casing at a weight ratio of casing to charge of one (M/C=1), the amount of energy given up to the metal is no longer available for the air blast wave. When the explosive detonates, it expands and then fragments the steel casing. Energy is transferred to the metal in three modes: shock heating, strain and fracture, and kinetic energy of the fragments.

**Table 3. EXPERIMENTAL AND CALCULATED TNT EQUIVALENTS
FOR AIR BLAST (data from Ref. 1, calculations by the author)**

EXPLOSIVE	Density (g/cm ³)	Heat of Explosion (cal/g)	CJ Pressure (GPa)	TNT Equivalence from Experiments (%)	Equivalence Calculated from Heat of Explosion	Equivalence Calculated from energy, PV, CJ state	Difference, PV calculation compared to Experiment (%)
NON- ALUMINIZED							
1. Ammon. Picrate	1.55	800	19.3	85	74	98	15.1
2. Amatol(60/40)	1.50	630	13.3	95	59	69	-26.9
3. Amatol(50/50)	1.55	700	16.4	97	65	84	-13.9
4. Comp A-3	1.59	1100	27.5	109	102	136	25.1
5. Comp B	1.68	1240	26.9	110	115	127	15.3
6. Comp C-3	1.60	1450	24.5	105	134	121	15.0
7. Cyclotol(75/25)	1.71	1230	28.3	111	113	131	18.4
8. Cyclotol(70/30)	1.73	1210	29.1	110	112	134	21.4
9. Cyclotol(60/40)	1.72	1200	27.8	104	111	128	23.4
10. Ednatol(55/45)	1.63	1340	23.0	108	124	112	3.3
11. Pentolite(50/50)	1.66	1220	24.2	105	113	115	9.7
12. Picratol(52/48)	1.63	1090	20.8	100	101	101	0.6
13. PTX-1	1.64	1520	25.2	111	141	121	9.3
14. PTX-2	1.70	1560	28.8	113	145	134	18.6
ALUMINIZED							
15. DBX	1.65	1700	18.8	118	157	90	-23.7
16. HBX-3	1.81	2110	22.3	116	195	98	-15.6
17. MINOL-2	1.68	1620	14.8	115	150	70	-39.2
18. MOX-2B	2.00	1470	11.3	102	136	45	-55.8
19. Torpex	1.81	1800	26.1	122	167	115	-5.9
20. Tritonal	1.72	1770	19.3	110	164	89	-18.8

**Table 3. EXPERIMENTAL AND CALCULATED TNT EQUIVALENTS
FOR AIR BLAST (data from Ref. 1, calculations by the author)**

The interaction of the detonation with the steel will produce a shock of about 32 GPa. This will heat the steel to about 300 degrees C. This takes around 35 calories for each gram of steel. The strain and fracture energy (depending upon the particular alloy) can be anywhere from 25 to 150 cal/g of steel. The fragments will be launched at around 1.9 km/s and their kinetic energy would then be around 415 cal/g. Since the M/C=1, for each gram of steel there was one gram of TNT. The PV energy available in the TNT is about 1160 cal/g, it gave up around a total of 500 cal/g to the steel. This leaves only around 660 cal/g to work on the air in the form of a blast wave, almost half of the original available energy. The shock heating, stated above, is dependent upon the CJ pressure of the explosive, increasing with higher CJ pressures. Therefore the energy lost to shock heating increases with increasing CJ pressure. Likewise, the energy lost to strain (expansion of the metal case) depends upon strain rate which increases with CJ pressure. The energy lost to fracturing depends upon the fracture surface area, and since increasing CJ pressure produces smaller fragments, the surface area and hence the energy losses in this mode increase with increasing CJ pressure. And lastly, the fragment velocity and hence the fragment kinetic energy increases with increasing CJ pressure. All of this means that as CJ pressure of the explosive increases, so likewise does the energy lost and not available for the blast wave. The implication here is that the differences seen in the prediction of TNT equivalence by the PV energy in the explosive should depend upon the CJ pressure, increasing (positive direction) with CJ pressures greater than that of TNT, and decreasing (negative direction) with CJ pressures below that of TNT. And indeed in Figure 6 we see that is so, where the differences in calculating the air blast TNT equivalence are plotted versus the CJ pressure of the explosives listed in Table 3.

Figure 6.
Percent difference between PV state energy calculations and TNT equivalence as measured in arena tests versus CJ pressure of the explosive tested

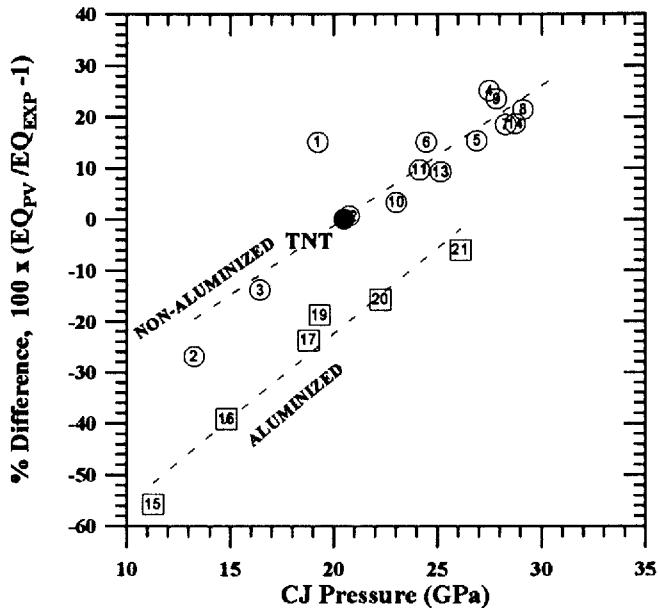


Figure 6. Percent difference between PV state energy calculations and TNT equivalence as measured in arena tests versus CJ pressure of the explosive tested

But we also see another large difference in predicting the experimental TNT equivalence by using the calculated energy in the PV state. This is the large difference between the aluminized and non-aluminized explosives, where calculations severely underestimate the results of the tests of the aluminized explosives. In order to try to understand why this so, we must again review where the energy comes from during detonation. It was stated earlier (in the section on the ballistic mortar tests) that in ideal explosives the chemical reactions take place and are completed within the CJ zone (or reaction zone). With non-ideal explosives part of the chemical reaction takes place behind the CJ zone, and that energy is therefore released slower than that from an ideal explosive. In aluminized explosives, part of the chemical energy is released very far back in the Taylor wave and some burning takes place so late that none of the chemical energy is recovered in the blast wave. By calculating only the CJ state conditions, the predictions above fail to include the later burning contributions. On the other hand, notice that the prediction of TNT equivalence of the aluminized explosives in these tests by using the calculated heat of explosion (Table 3) systematically overestimates the test results. This apparently is because not all of the aluminum is burning, or that only a portion is burning at a sufficiently high pressure to contribute to the blast wave. So we see that we cannot predict by simple calculations the TNT equivalence, or the actual pressure for that matter, of highly non-ideal or metalized explosives, because we cannot account for the way

that reactions occur after the CJ zone. In fact, we cannot model this phenomenon even with our best hydrocodes on huge computers because we do not yet have equations of state for detonation products which include these late time chemical reaction effects.

Air Blast prediction gets even more complicated. As a blast wave proceeds through the air the peak pressure decays and the pulse width increases. The changes in shape and pressure for an idealized blast wave produced by a one kilogram spherical charge of TNT as it proceeds through the air are shown in Figure 7. The calculations to generate this figure were based upon equations and data given in Ref. 5. Notice that the rate of decay of the peak pressure decreases as the slope of the expansion wave decreases. This is very important because if the initial expansion wave from a given explosive has a shape which is not identical to that of TNT, the peak pressure of the resultant blast wave will decay at a different rate than that of TNT. What this means is that the TNT equivalence for that explosive will vary with distance. Small changes in slope along the expansion wave will result in rising or falling TNT equivalence when that part of the wave catches up with the shock front. This effect is seen in Figure 8, where data for TNT equivalence (from Ref. 6) is given as a function of the scaled distance for five different explosives. Figure 9 shows data for the blast wave produced by a 17.5 gram charge of a pyrotechnic (Al/KClO₄) which is on the borderline of detonation and is highly non-ideal (data from Ref 4).

Figure 7. The progress of a blast wave through air produced by a 1.0 kg spherical charge of TNT

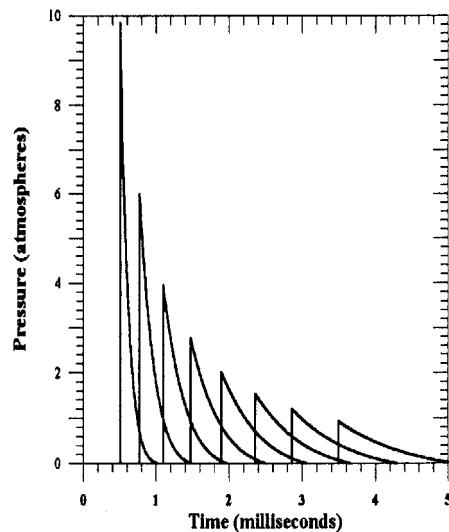
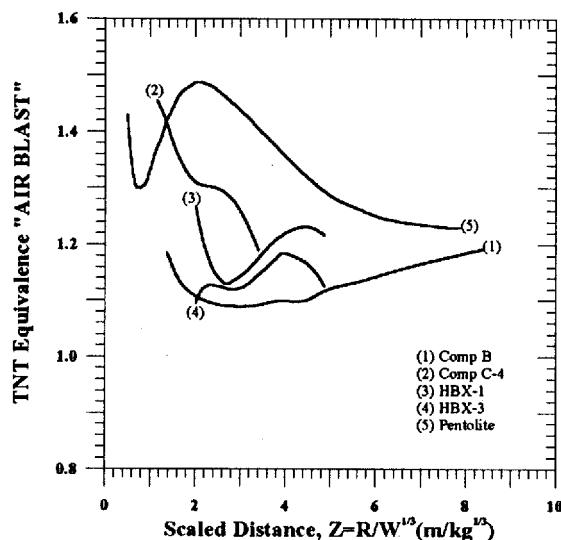


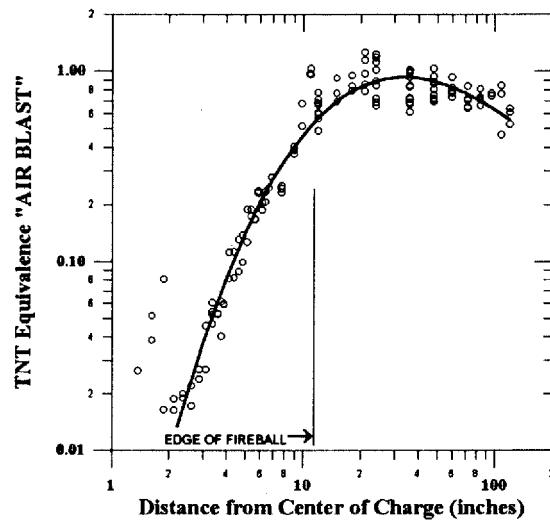
Figure 7. The progress of a blast wave through air produced by a 1.0 kg spherical charge of TNT

Figure 8.
Variation of TNT Equivalence with scaled distance for five explosives



**Figure 8. Variation of TNT Equivalence
with scaled distance for five explosives**

Figure 9.
Variation of TNT Equivalence with distance, 17.5 g charge of Al/KClO₄



**Figure 9. Variation of TNT Equivalence
with distance, 17.5 g charge of Al/KClO₄**

Note from Figure 8 that the range of variation of TNT equivalence with distance may be as high as 25 percent. At first this seems that scaling predictions using TNT equivalence as a base will be very poor, but it must be remembered that in scaling calculations the cube root of the explosive weight is the governing term and this potential error therefore reduces to no worse than about 7 percent.

CONCLUSIONS

We have seen that the term "TNT Equivalence" has little practical meaning in respect to most of the tests which are used in the attempt to define it. For applications where our interest is in understanding and quantifying the effects of explosives which apply to shattering and/or producing plastic deformation of an adjacent material, the CJ pressure of the explosive is the precise property which is applicable. This property can be easily and accurately calculated once the density and detonation velocity are known, and these are parameters which are relatively easy to measure. The dent test is another way to obtain a reasonable measure of the CJ pressure.

For the purposes of predicting blast or cratering or blast effects on structures or for the estimation of physiological response to blast, TNT equivalence is certainly usable and is our only common engineering tool available. It should be remembered however that there are large, yet workable, errors inherent in the experimental determination of TNT equivalence as well as in the calculations which are used to estimate the equivalence from other explosive properties.

Existing computer codes cannot accurately predict blast waves due to the lack of chemically reactive equations of state. Perhaps this is an area which should have more attention.

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